

Multiband Comparative Study of Optical Microvariability in RL vs. RQ Quasars

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ABSTRACT

We present the results of an optical multi-band (BVR) photometric monitoring program of 22 core-dominated radio-loud quasars (CRLQs) and 22 radio-quiet quasars (RQQs). The aim was to compare the properties of microvariability in both types of quasars. We detected optical microvariability in 5 RQQs and 4 CRLQs. Our results confirm that microvariability in RQQs may be as frequent as in CRLQs. In addition we compare microvariability duty cycles in different bands. Finally, the implications for the origin of the microvariations are briefly discussed.

Subject headings: galaxies:active- quasars:general-galaxies:photometry-galaxies:fundamental parameters

1. INTRODUCTION

Optical Microvariability (OM hereafter) defined as flux changes on timescales ranging from minutes to hours, and with amplitudes that range from a few hundredths to a few tenths of a magnitude, was reported almost simultaneously as the quasar discovery (Matthews & Sandage 1963; Oke 1967). However, those reports were ignored or skeptically attributed to instrumental and/or weather causes. Nowadays, with the CCD technology, and better statistical techniques, there is no doubt about the reality of OM.

The importance of OM studies resides on the opportunity that they provide to set limits on the size of the emitting regions, to constrain emission models, and to probe physical conditions in the innermost regions of active galactic nuclei (AGN), very close to the central black hole. Some OM studies have been carried out to investigate its incidence in radio quiet quasars (RQQs) as compared to radio loud quasars (RLQs) (Jang & Miller 1997; Romero et al. 1999; Stalin et al. 2004; Gupta & Joshi 2005;

Stalin et al. 2005; Carini et al. 2007; de Diego et al. 1998, hereafter Paper I). The motivation for searching OM in RQQs and compare its incidence with OM in RLQs, is to identify the source of OM and try to constrain the most probable models: accretion disk and/or jet emission (e.g. Lightman & Earley 1974; Blandford & Königl 1979; Marscher & Gear 1985; George & Fabian 1991; Qian et al. 1991; Marscher et al. 1992; Gopal-Krishna et al. 1993a,b; Mangalam & Wiita 1993; Chakrabarti & Wiita 1994; Krishan & Wiita 1994).

Some of these studies have found that OM occurs in quasars regardless of their radio properties. The results reported by Stalin et al. (2004) indicate that although strong radio emission does not guarantee microvariability generation the most variable objects are those with more intense radio emission. On the other hand, Carini et al. (2007) found a higher instance of OM in radio-loud quasars than in radio quiet quasar. According to these results, orientation could play a fundamental role. Thus, objects with jets aligned closer to the line of sight are those with larger

duty cycles and amplitudes. On the other hand, in Paper I we showed for the first time that microvariability is a phenomenon as common in radio quiet quasars (RQQs) as in core-dominated radio loud quasars (CRLQ), thus indicating that OM in quasars is independent on the radio properties, pointing to a discrepancy with respect to the orientation scheme.

The orientation scheme assumes that OM is generated in the jet. Even if only to test this scheme it is relevant to investigate whether OM does indeed origin in the jet, the accretion disk, or both. Disk phenomena are mostly related with thermal processes such as hot spots or other disk instabilities, while jet emission is associated with non-thermal activity such as the relativistic particle ejection events at the base of the jet. So in principle we can distinguish the OM origin, if we can identify the OM event as the result of a thermal or a non-thermal phenomenon. We will propose below a color study that can help us find some distinctive characteristic of the variable component, which can be seen in the variations in the shape of the continuum spectrum.

The paper is organized as follows: we begin in Section 2 by describing the observations, the data treatment, and the selection criteria. In Section 3 we show the results for the detected microvariations. In Section 4 we discuss these results, and finally we summarize our work and give conclusions in Section 5.

2. SAMPLE SELECTION, OBSERVATIONS AND DATA REDUCTION

Because selection effects may yield unwanted biases in the study of OM, we have minimized them using the same selection criteria as in Paper I. Briefly, two quasar samples were observed and compared: one constituted by 22 RQQs, and a control sample conformed by 22 RLQs (see Table 1). The samples were chosen in such a way that for each RLQ there is a RQQ with similar brightness and redshift (differing less than 10%), avoiding possible evolution biases between the samples. To avoid orientation biases, RLQs chosen are all core-dominated RLQs (CRLQs), but avoiding to include objects extremely variables such as known blazars. When this sample was assembled, PKS 1510-089 was not considered a blazar,

although now it is indeed. Unfortunately, it is hard to avoid the possibility to contaminate a sample of radio loud quasars by blazars, due to better/new observations, particularly in other frequencies. Nevertheless, we will show in a forthcoming paper (Ramírez et al. in preparation) that the OM detected in this object presents characteristics that differ of those associates to blazars. For this reason, we prefer to keep it in our sample. Choosing CRLQs instead of RLQs is a simple way to avoid unknown orientation effects in the sample. Thus, the CRLQs are expected to be as homogeneous as possible from the observational point of view, while their intrinsic physical properties are a truthful representation of the RLQs population. All the objects in the CRLQs sample have radio to optical flux ratio near or above 1000, computed from the 408 MHz to *V*-band, thus they belong to the RLQ population after Falcke et al. (1996) criterion. Table 1 shows the complete sample. A number identifies each couple (col. 1), "a" refers to RQQ component and "b" to CRLQ; the object name (col. 2); the coordinates (J2000.0) of each one (cols. 3 and 4); the reported average magnitude in the *V* band (col. 5) and the redshift (col. 6).

Observations were made in several seasons, between 1998 and 2002, with four telescopes distributed in Mexico and Spain. In Mexico, two telescopes, of 1.5-m and 2.1-m, were used (Mx1 and Mx2, hereafter, respectively). These are operated by the Observatorio Astronómico Nacional (OAN), located in San Pedro Martir, Baja California. Observations in Spain were made using two telescopes. The 1-m Jacobus Kapteyn Telescope (JKT), located in the Roque de los Muchachos Observatory, and operated by the Isaac Newton group. We also used the 1.5-m telescope at the Estación Observacional de Calar Alto (EOCA), located in the Astronomical Hispanic-German Centre in Calar Alto (CAHA), which is operated by the Spanish Observatorio Astronómico Nacional.

Filters *BVR* of the Johnson-Cousins series were used throughout all the observations. The detectors used were: in Mx1, a SITE SI003, 1024×1024 pixels of 24- μm^2 which has a methacrome II cover and a VisAr, to improve the response in the blue; in Mx2, a Thomson TH7398 2048×2048 pixels of 24- μm^2 which has a methacrome II cover; in JKT, a TEK1024AR constituted by 1024×1024 pixels

Table 1:: The sample.

Pair		R.A.	DEC.	V	z
ID	object	(J2000.0)	(J2000.0)		
1a	US 1867	08:53:34	+43:49:01	16.4	0.513
1b	3C 334.0	16:20:21	+17:36:29	16.4	0.555
2a	1628.5+3808	16:30:13	+37:58:21	16.8	1.461
2b	3C 298	14:19:07	+06:28:35	16.7	1.439
3a	1222+023	12:25:17	+02:06:56	17	2.05
3b	PKS 0421+019	04:24:08	+02:04:30	17	2.048
4a	1E 15498+203	15:52:02	+20:14:02	16.5	0.25
4b	PKS 1217+02	12:20:11	+02:03:42	16.5	0.24
5a	US 737	09:35:02	+43:31:12	16.3	0.456
5b	PKS 1103-006	11:06:31	-00:52:52	16.4	0.426
6a	0214-033	02:17:29	-03:08:08.6	16.8	0.323
6b	PKS 2208-137	22:11:24	-13:28:09.7	17	0.39205
7a	CSO 233	09:39:35	+36:40:01	17	2.03
7b	PKS 1022-102	10:24:56	-10:31:44	17	2
8a	CSO 21	09:50:45	+30:25:19	17	1.19
8b	PKS 1127-14	11:30:07	-14:49:27	16.9	1.187
9a	TON 156	13:21:16	+28:47:19	16.6	0.549
9b	PKS 1327-21	13:30:07	-21:42:04	16.7	0.528
10a	TON 133	12:51:00	+30:25:42	17	0.56
10b	3C 281	13:07:53	+06:42:13	17	0.599
11a	CSO 18	09:46:36	+32:39:51	17	1.3
11b	PKS 0514-16	05:16:15	-16:03:08	16.9	1.278
12a	E 0111+388	01:13:54	+39:07:45	16.7	0.234
12b	PKS 2247+14	22:50:25	+14:19:50	16.9	0.237
13a	MRK 1014	01:59:50	+00:23:41	15.6	0.163
13b	PKS 2349-01	23:51:56	-01:09:13	15.3	0.173
14a	Q0050-253	00:52:44	-25:06:51	16.1	0.626
14b	PKS 2243-123	22:46:18	-12:06:51	16.4	0.63
15a	US 3150	02:46:51	-00:59:31	16.8	0.467
15b	PKS 0003+15	00:05:59	+16:09:49	16.4	0.45
16a	US 3472	02:59:38	+00:37:36	16.6	0.532
16b	PKS 0122-042	01:24:34	-04:01:05	17	0.561
17a	MRK 830	14:50:26	+58:39:44.8	16	0.21
17b	OX 169	21:43:35	+17:43:49.5	15.7	0.213
18a	PG 1444+407	14:46:46	+40:35:06.0	15.6	0.267
18b	PKS 2135-14	21:37:45	-14:32:55.1	15.5	0.2
19a	PG 1543+489	15:45:29	+48:46:09	16.4	0.4
19b	PKS 1510 -08	15:12:50	-09:05:60.0	16.5	0.361
20a	MC3 1750+175	17:52:46	+17:34:20.3	15.5	0.507
20b	PKS 2128-12	21:31:35	-12:07:04.5	16.1	0.501
21a	PG 1538+477	15:39:33	+47:35:33	16	0.77
21b	PKS 1424-11	14:27:37	-12:03:54	16.4	0.805
22a	PG 1407+265	14:09:23	+26:18:18	15.9	0.944
22b	PKS 2145+06	21:48:05	+06:57:35	16.4	0.99

Radio quiet quasars are identified with the letter a;
radio loud quasars are identified with a letter b.

of $24\text{-}\mu\text{m}^2$ was used, this chip is covered with Ar; and, in the EOCA telescope, a CCD Tektronics TK1024AB of 1024×1024 pixels of $24\text{-}\mu\text{m}^2$. In all the cases the detectors were binned to allow for a fast and low noise readout.

The observational strategy was performed using an *Analysis of Variance* (ANOVA) design, similar to the one described in Paper I, but considering three filters instead of only one. Shortly, each time that an object was observed, it was recorded in five observations of ~ 1 -minute exposure each, in each filter in the sequence *BVR*, except for a couple of cases, where the sequence was inverted to *RVB*. It was possible to monitor from 2 to 4 pairs per night, and 2 to 5 times each pair. Each object was observed at moderate air masses, always at least 30 degrees above the horizon. The magnitude difference errors were obtained directly from the observations by means of the differential photometry. These errors range typically from ~ 0.001 to 0.01 instrumental magnitudes. Additionally, each pair was observed on the same nights and in overlapping sequences, to avoid possible biases due to atmospheric and/or instrumental conditions.

Previous to the extraction of data, images were corrected for bias and flat fields. The flat fields were sky flat-fields acquired at the beginning and/or end of every night. Objects were observed, insofar as possible, when they were meridian crossing, minimizing color effects by the atmospheric extinction. For each object, field-stars were used as comparison and reference stars to obtain differential photometric data used in the posterior analysis; typically, from four to eight stars were used (except for a couple of cases where we only had two stars). The selected stars were those that remained stable during the observations at a 20% confidence level. Here the results with only two of them will be shown. Unlike Paper I standard stars were observed to obtain the flux level of the observed objects as well. These stars are all taken from Landolt (1992).

The IRAF/APPHOT¹ package was used to perform data reduction. The aperture radii used ranged from three to six arcseconds, while the

¹IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

size of the sky annuli was of 10 arcseconds for the inner radius, and 16 arcseconds for the outer radius. When the host galaxy was detectable, we took a sufficiently large aperture to avoid effects due to the seeing. This was done although Carini & Miller (1991) and Clements & Carini (2001) found that the host galaxy cannot provoke false microvariations due to light that *enters and leaves* the aperture (see also Kidger & de Diego 1992). However, Cellone, Romero & Combi (2000) found that the host can influence spurious variations detection, but only under extreme atmospheric conditions (with FWHM variations of ~ 5 arcseconds) for galaxies as bright as the nucleus. Similar conditions were absent in our study.

3. RESULTS

Searching for microvariability for each object was done with the ANOVA, particularly, the one-way ANOVA test was utilized. Contrary to a *standard test*, where the object standard deviations are analyzed with respect to comparison stars (e.g., $\sigma_{obj}/\sigma_{est} = 2.576$, for detection of variability, Jang & Miller 1997; Romero et al. 1999), ANOVA is an empirical very robust statistical test. We used a significance level of 0.1% (corresponding to 3σ) for the one-way ANOVA test as variability criterion, although for some objects, in some filter, we will discuss also possible variations considering 3% and 5%. The functional procedure on the ANOVA test is given in the next lines.

We have implemented One-Way ANOVA to search for variability comparing data measured in k groups of observations sampled from a quasar lightcurve. If y_{ij} represents the value of the i th observation ($i = 1, 2, \dots, n_j$; note that we have chosen $i = 1, 2, \dots, 5$ for all the groups) on the j th group ($j = 1, 2, \dots, k$), we can express a mathematical model describing each single observation:

$$y_{ij} = \bar{y} + g_j + \varepsilon_{ij}$$

where \bar{y} is the mean of the whole dataset, g_j is the between-groups deviation ($g_j = \bar{y}_j - \bar{y}$) and ε_{ij} the within-groups deviation, often called residual or measurement error ($\varepsilon_{ij} = y_{ij} - \bar{y}_j$).

ANOVA tests whether the means of the groups are equal. Statistically, this can be expressed saying that the null hypothesis (i.e., the hypothesis that we are testing) is that the means of the different groups are the same, and the alternate hy-

pothesis (i.e., the hypothesis that we will accept if the null hypothesis would be rejected) is that at least one group has a mean different from the others. In our case, the alternate hypothesis implies a microvariability detection.

Following the implicit mathematical model of ANOVA, the total sample variation can be split into variation *between* and *within* groups:

$$\sum_{j=1}^k \sum_{i=1}^{n_j} (y_{ij} - \bar{y})^2 = \sum_{j=1}^k n_j (\bar{y}_j - \bar{y})^2 + \sum_{j=1}^k \sum_{i=1}^{n_j} (y_{ij} - \bar{y}_j)^2,$$

where the left term is a measurement of the total deviations of the data with respect to the mean, the second term measures the total variation between groups, and the third term the total errors. The equation can be abbreviated to:

$$SS_{Total} = SS_{Group} + SS_{Error}.$$

When the null hypothesis is true, the k groups sample data will be normally and independently distributed, with mean μ and variance σ^2 . Thus the statistic:

$$F = \frac{MS_{Group}}{MS_{Error}} = \frac{SS_{Group}/(k-1)}{SS_{Error}/(N-k)},$$

will follow an F distribution with $k-1$ and $n-k$ degrees of freedom, and where the *pseudo* variances MS_{Group} and MS_{Error} are mean estimates for the variations between groups and errors, respectively. Given a certain significance level α , if the F statistic exceeds the critical value $F_{(k-1, n-k, \alpha)}$ the null hypothesis should be rejected.

The rest of this section is devoted to describe the results, object by object, for those cases where variability was detected. In Figures 1 we show the light curves for differential photometry for each object. Symbols represent the mean for each group of five observations of each object (left panel) and the stars (right panel). Error bars correspond to a standard error toward each side, and they were calculated from the dispersion of each group.

From a total of 130 observations, we detected 9 microvariability events, and 2 possible ones, in eight out of 44 observed objects, three CRLQs and five RQQs. Two quasars displayed microvariability in more than one night: the CRLQ 3C 281 was

observed to vary in two nights, while microvariability in Mrk 830 was detected one night, and probably were present in two more occasions.

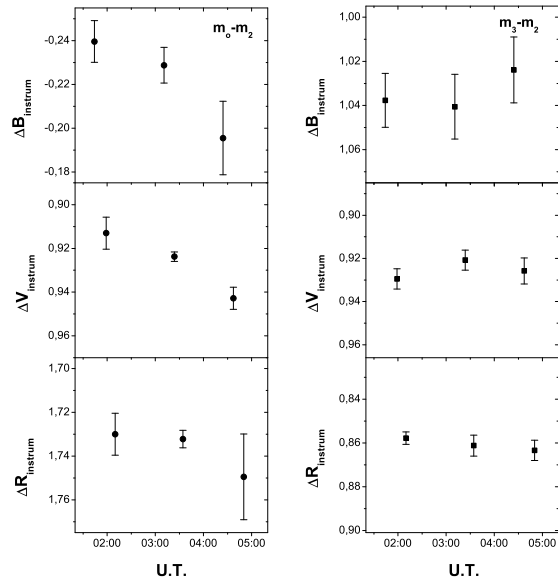
3.1. Radio Loud Quasars

3C 281.- This radio loud quasar is known to reside in a very rich galaxy cluster (Yee & Green 1987). A variation of 0.15 magnitudes in one year has been reported in the infrared (Enya et al. 2002a,b). We observed this object for Paper I on May of 1997, but microvariability was not detected. We observed this quasar with EOCA on 2000 March 1 and 4, detecting OM events in both nights.

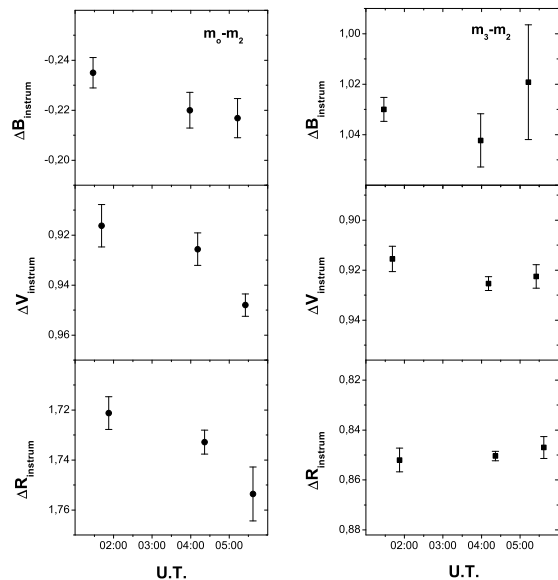
2000 March 1.- The object was observed during 2.7 hours three times. A visual analysis of the light curves shows a decrease in brightness of almost 4 hundredths of a magnitude (Figure 1(a)). ANOVA confirms a microvariation in B and V , detectable at a 0.1% significance level, but not in R . This detection is appreciated with all the available stars. In V , the amplitude is $\Delta V = 0.031 \pm 0.007$ mags, in 2.7 hrs, while between the second and third groups $\Delta V = 0.024 \pm 0.007$ mags, in ~ 1 hour. In B , the amplitudes are $\Delta B = 0.05 \pm 0.01$ mags between the first and the third observations and $\Delta B = 0.03 \pm 0.01$ mags between the second and the third.

2000 March 4.- 3C 281 was observed during 3.75 hours in three occasions. A visual revision of the light-curves establishes the occurrence of a possible variation in the three bands (Figure 1(b)). However, ANOVA only detected a variation in V and a marginal one in R (with a significance level of 5%). The variation amplitude is $\Delta V = 0.027 \pm 0.006$ mags between the first group and the third.

PKS 1510-089.- This RLQ has shown intense activity on long and intermediate-term variability (Liller & Liller 1975; Tornikoski et al. 1994; Villata et al. 1997), as well as correlated optical/radio variability (Tornikoski et al. 1994). OM also has been reported (Villata et al. 1997; Xie et al. 2001; Dai et al. 2001; Xie et al. 2004). In particular, Dai et al. (2001) reported a variation of 2 mag in 41 minutes in R band at the end of 2000 May. However, Romero et al. (1999) and Romero et al. (2002) did not detect any activity when they observed it between 1998 and



(a) 3C 281, 2000 March 1



(b) 3C 281, 2000 March 4

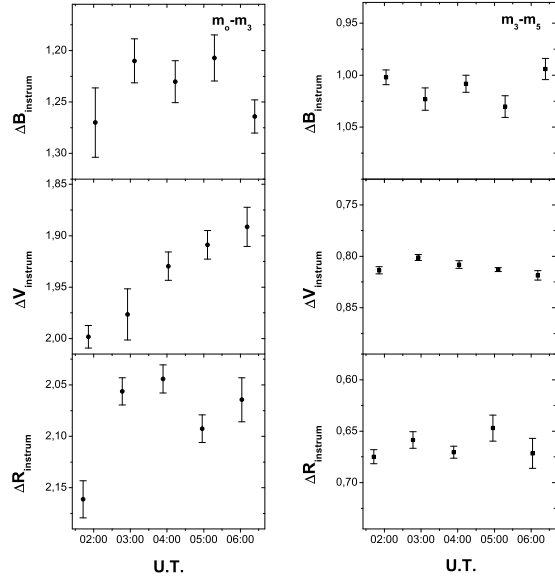
Fig. 1.—: Light curves for the objects discussed in the text. In each Figure, left panel shows the data for the quasar, while right panel for the comparison stars. Symbols represent average values of five consecutive observations, and the error bars have been estimated from data dispersion. Footnote of each Figure indicates the quasar name and the observation date.

1999. Our observations show that PKS 1510-089 was in a stage of activity during the first semester of 2000. We monitored this object during 4.3 hours in 5 different occasions during the night of 2000 March 20 (two months before the observations of Dai et al. 2001). Light-curves (Figure 1(c)) indicate the presence of an OM event detected in V and R . While a progressive increase in brightness is detected in V , a variation is observed between the first and the second datasets in R , which remains in the same level of brightness the rest of the session. ANOVA agrees with the visual revision of Figure 1(c). This variation is confirmed with a 0.1% level of significance. The comparison between the stars indicates that they do not vary. In V , the microvariation seems to evolve during the 4.3 h of observation, with a total amplitude of 0.104 ± 0.014 mags (with respect to the first data set changes are: $\Delta V = 0.03 \pm 0.02$ mags in 1 hour, $\Delta V = 0.07 \pm 0.01$ mags in 2.2 hours, and $\Delta V = 0.09 \pm 0.01$ mags in 3.25 hours). In R , the amplitude between the first dataset and the average of the subsequents is $\Delta R = 0.108 \pm 0.008$ mags. From the light-curves, it is clear that color changes occurred during this OM (see Figure 1(c)).

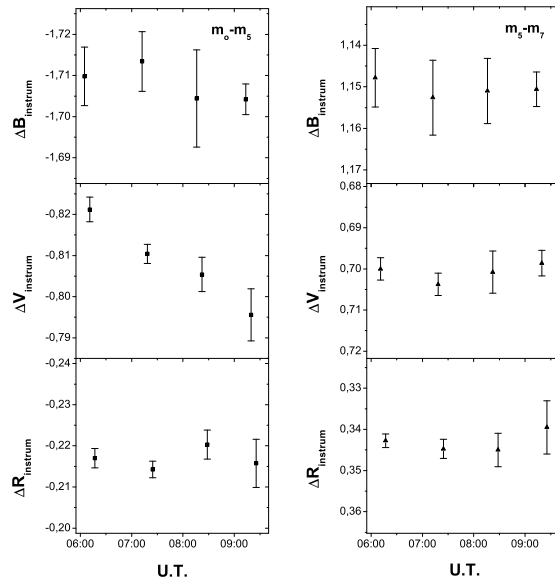
PKS 0003+15.- Historically, this quasar has shown intense activity on long-term and intermediate-term variability (Barbieri et al. 1979; Pica et al. 1988; Schramm et al. 1994; Guibin et al. 1995, 1998; Garcia et al. 1999). OM has also been detected. On October of 1994, Jang & Miller (1995) observed a variation in R with an amplitude of 0.11 mags in 2 hours, while Eggers et al. (2000) reported changes of 0.005 mag/h in R . Garcia et al. (1999) also reported microvariability for this quasar. PKS 0003+15 was reported in Paper I with no evidence of microvariability. We have monitored this quasar during 3.13 hours in four occasions on October 11 2001. Figure 1(d) shows that while brightness remained constant in B and R , a decrement in V was detected. ANOVA confirms this visual revision. The brightness for this object showed a decrease of $\Delta V = 0.025 \pm 0.005$ mags during the monitoring time.

3.2. Radio Quiet Quasars

MC3 1750+175.- The only variability event previously reported for this quasar corresponds to radio wavelengths (Fanti et al. 1981; Mantovani



(c) PKS 1510-089



(d) PKS 0003+15

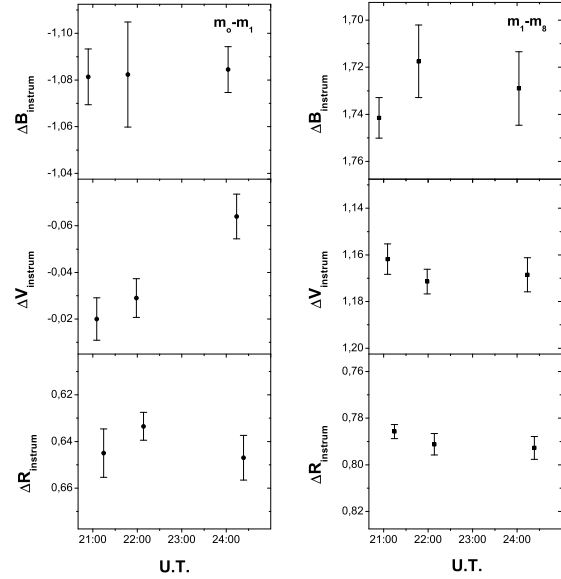
Fig. 1.—: Continued.

1982). On 1999 August 20, we observed this object three times during 3.13 hours. The light-curves show a microvariability event only visible in the V band (Figure 1(e)). ANOVA confirms this appreciation, the amplitude of this variation is $\Delta V = 0.04 \pm 0.008$ mags between the first dataset and the third.

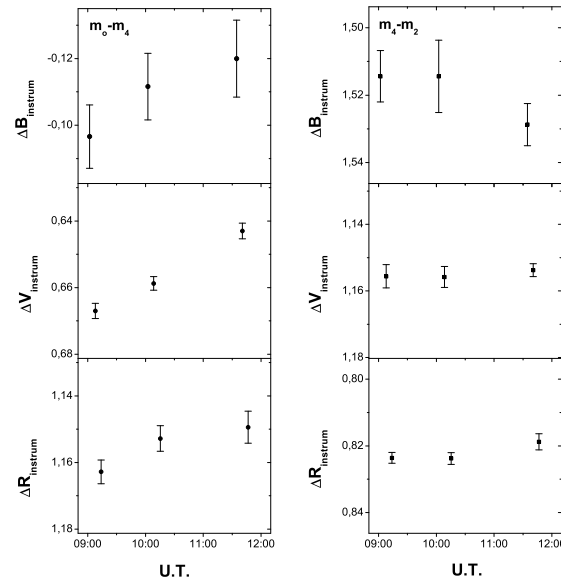
CSO 21.- Observations for CSO 21 were reported in Paper I, but without a positive detection of microvariability. For the present study, the object was observed in three occasions on 2001 December, during 2.5 hours. A gradual brightness increase is appreciated in the three bands (Figure 1(f)). However, ANOVA indicates a variation in V only, a barely marginal variation in R (with a significance level of 10%), and no variation in B (if the observed tendency in the B light-curve is a variation, it is hidden by the internal data dispersion). The amplitude of the variation is $\Delta V = 0.025 \pm 0.005$ mags in 2.5 hours. Variation amplitude of the R band is $\Delta R = 0.016 \pm 0.004$ mags between the first dataset and the third.

1628.5+3808.- In Paper I we reported the cases of microvariability for this object for the first time. They are two events on 1997 February an May. In February, a variation with amplitude of 0.082 mags throughout 2.4 hours; while in May, throughout six monitoring hours, the OM consisted of pulsations with amplitudes from 0.04 to 0.057 mags. We observed this quasar in two occasions on 2001 June 13. The light curves show an appreciable brightness decrease in the three bands (Figure 1(g)). ANOVA indicates that this variation is detectable in the B and R , but in V the variation is only marginal (the significance level is 3%). The data dispersion in the comparison stars do not show evidence for statistical differences. The OM amplitudes are $\Delta B = 0.061 \pm 0.011$ mags and $\Delta R = 0.018 \pm 0.004$ mags, in the 2.39 hours of monitoring. The V marginal detection would have an amplitude of 0.03 ± 0.01 mags.

US 3472.- In Paper I we reported an OM event for this quasar with an increase of 0.02 mags in 50 minutes. During 2 hours, a series of oscillations followed to this brightness increase, with amplitudes between 0.040 and 0.055 mags. Long-term optical and infrared variability has also been reported (Enya et al. 2002a). We observed this object during 2.5 hours in three occasions on 2001 December 20. The light-curves show a brightness

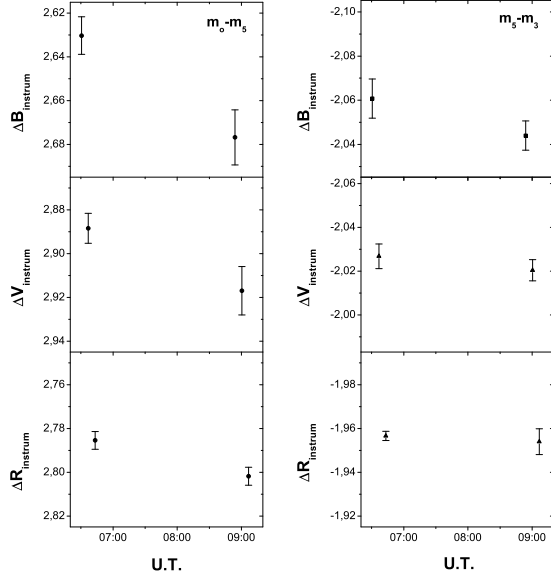


(e) MC3 1750+175

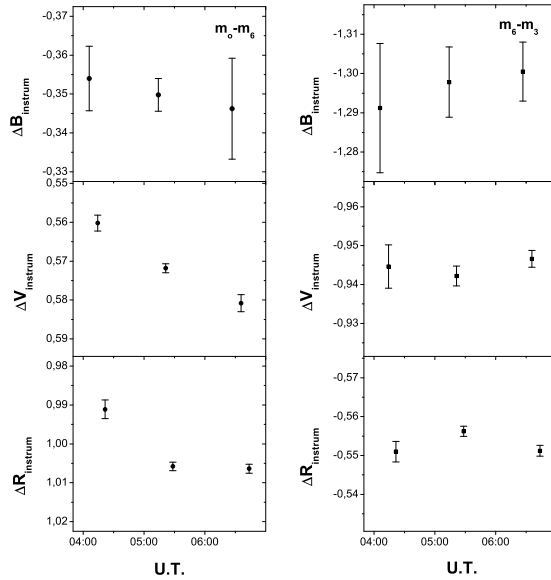


(f) CSO 21

Fig. 1.—: Continued.



(g) 1628.5+3808



(h) US 3472

Fig. 1.—: Continued.

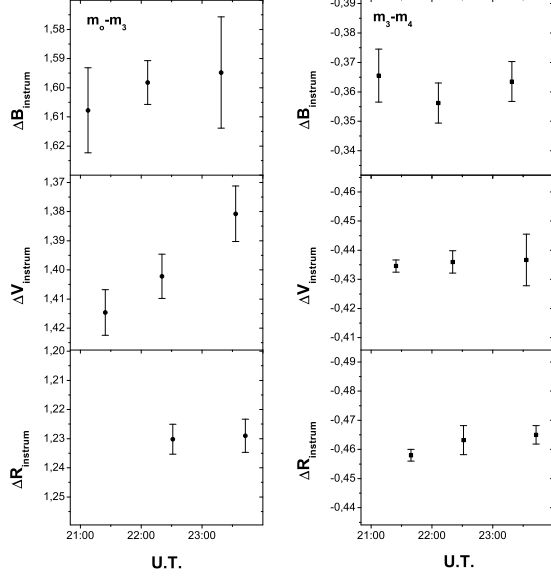
decrease in V and R (Figure 1(h)). ANOVA confirms the variation. In V , the microvariation seems to have kept a constant rate with a total amplitude of $\Delta V = 0.020 \pm 0.003$ mags in 2.35 hours. Between the first and the third dataset in the R band, the brightness varied by 0.014 ± 0.002 mags.

Mrk 830.— Long- and short-term variability, and microvariability have been reported for this quasar. We observed this object in four different occasions, OM events being detected on 1999 August 17 and 18, and on 2001 June 14. The object possessed a brightness very similar on the three occasions, $V \sim 17.6$. This brightness is similar to that reported by Stepanian et al. (2001) ($V = 17.29 \pm 0.03$), and Chavushyan et al. (1995) ($V = 17.62$). Unfortunately, the fields of the two telescopes used are different, and thus it was more convenient to use a different set of comparison stars for the August of 1999 and the June of 2001 observations.

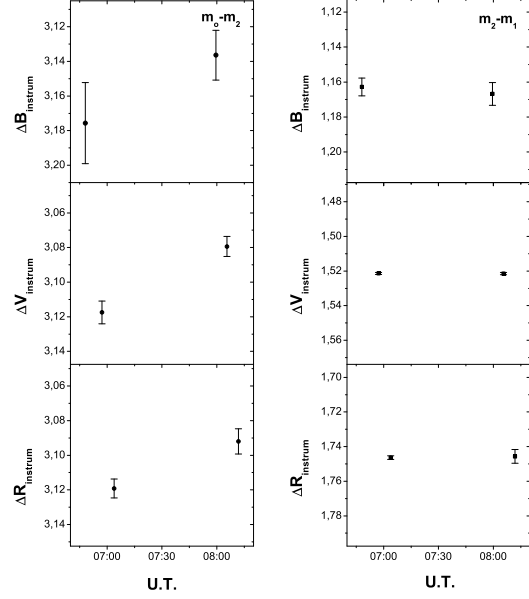
1999 August 17.— The object was observed during 2.13 hours in three times. A visual revision of the light-curves indicates the possible detection of a microvariability event in V (Figure 1(i)). Due to instrumental problems, in the first sequence of the R band, we missed the object for several images. Thus we can present only the complete curve for the comparison stars. ANOVA shows that this variation would be marginal, with a significance level of 3%. The increment in brightness, if real, has a constant rate with a total amplitude of $\Delta V = 0.03 \pm 0.01$ mags in 2.31 hours.

1999 August 18.— The monitoring dataset consisted on three observation groups taken during two hours. Again, a revision of the light-curves shows a possible variation in V (Figure 1(j)). ANOVA detects this feature as a marginal variation, with a significance level of 3%. As on the previous night, the tendency is a variation at a constant rate, but in this time with a total amplitude of $\Delta V = 0.05 \pm 0.03$ mags.

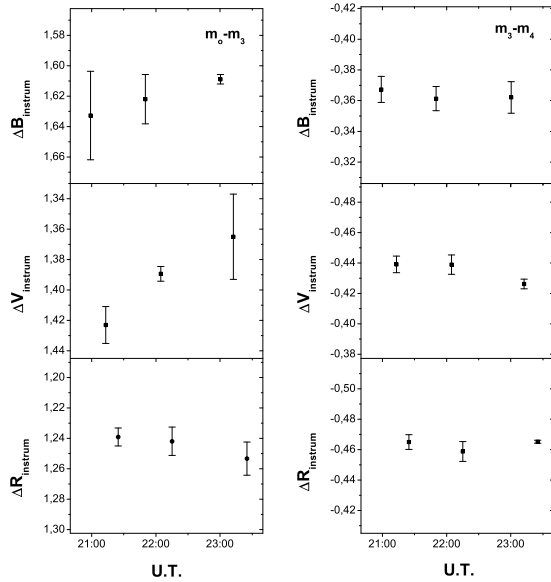
2001 June 14.— On this night the quasar was observed twice. A visual revision of the light-curves indicates a possible variation in the three bands (Figure 1(k)). The brightness increase is a few hundredth of magnitude between the two groups of observations. ANOVA confirms the reliability of this variation. While in V and R the significance level is 0.1%, in B the value is $\sim 5\%$. The amplitudes are $\Delta V = 0.039 \pm 0.007$ mags and



(i) Mrk 830, August 17 1999



(k) Mrk 830, June 14 2001



(j) Mrk 830, August 18 1999

Fig. 1.—: Continued.

Fig. 1.—: Continued.

$\Delta R = 0.030 \pm 0.007$ mags, occurring during 1.18 hours. If a variation exists in B , the amplitude would be of $\Delta B \sim 0.04$ mags.

4. DISCUSSION

An immediate result of this work is that microvariability is a more complex phenomenon than appreciable in single optical band studies. The different color evolutions during microvariability events will be analyzed in a forthcoming paper (Ramírez et al. in preparation). In this section we will compare statistically the results of OM obtained from the two samples of RQQs and CRLQs. The aims are twofold: 1) to find inferences on the populations of which the samples have been extracted when comparing each pair of objects, and 2) to describe the probability of detecting a microvariability event as a function of the duration of the observation for each object. Several well-known statistical tests are applied to attain these objectives. Some of these tests deal with the qualitative properties of the results, such as detection or non-detection of OM (§ 4.1), and others deal

directly with the numerical results (§ 4.2). Because of the differences in the variability detected for each band, the numeric tests were carried out separately.

Statistical tests are described in detail in Paper I. Shortly, a χ^2 test for homogeneity is used to compare the occurrence of OM events between the CRLQs and the RQQs samples. Using this test, one can determine if a quasar type presents a statistically larger number of OM events than the other. On the other hand, a quantitative test on the differences among the samples is carried out through the comparison of the variances of the paired objects. The observed variance was considered to arise from two different error sources: one corresponding to the observational error and another due to the intrinsic variance of each object (see Paper I for details). Then a couple of statistical tests were applied to the mean of the differences of intrinsic variances of RQQs and CRLQs: a *t-Student* matched pair test and an independent sample test. At the end of the section, the microvariability occurrence as a function of monitoring time, i.e., the duty cycle will be analyzed.

The variations showed in Figs. 1(c) and 1(d), for PKS 1510-089 and PKS 0003+15, respectively, differ very much in different bands. However, these variations can be explained in the context of emission models. We will explain such variations in a forthcoming paper (Ramírez et al. in preparation).

4.1. χ^2 Test for Homogeneity

The χ^2 test for homogeneity is used to compare two or more qualitative properties of several samples when the number of elements in each sample is fixed. In our case, we will split the observations of the two samples of RQQs and CRLQs into those that show variability and those that do not.

For each sample of RQ and CRL objects the microvariability events were counted regardless of the band of detection. As in Paper I we note that although each observation will be considered independently, some of them may belong to the same object. In doing this, some unwanted effects can be introduced because the observations of the same object may not be completely independent. This may be the case, for example, if one object is intrinsically much more variable than another.

The total number of paired observations for each sample is 63 (although the number differs for each band, i.e., the occasions in which one could observe the two members of the same pair were 61 for *B*, 63 for *V* and 61 for *R*). In 9 of these monitoring microvariability was detected for at least one member of each pair, with a significance level of 0.1%. Five out of these 9 were detected in RQQs and four in RLQs. This number rises to 11 when we take into account the two marginal detections of Mrk 830.

Table 2 shows the χ^2 contingencies for these data. Column 1 displays the number of OM events with a significance level of up to 0.1%. The number of observations in which there are no evidences of variability appear in column 2, the total number of observations appear in column 3, and the expected frequencies of microvariations under the null hypothesis, i.e., if both types of objects possess the same microvariability properties, are shown in columns 4 and 5. These last columns are calculated multiplying the partial totals of each line and each column and then dividing by the total number of observations. The homogeneity test shows that the probability of observing the numbers in Table 2 can be obtained 27% of the times when extracting two samples in an aleatory way from the same population. The probability to obtain the observed OM frequencies is large enough and thus the null hypothesis cannot be rejected. In other words, it is reliable to assume similarity between the two samples.

Table 2:: χ^2 contingencies table.

Quasars	Observed		Total	Prospective	
	V	NV		V	NV
RQQ	5	58	63	4.5	58.5
CRLQ	4	59	63	4.5	58.5
Total	9	117	126	9	117

Contingencies Table to compare the radio properties of the microvariability of the two quasars samples. It does not seem to have any difference when the three filters are considered. This result indicates that optical microvariability is a common phenomenon to the object classes. $\alpha = 0.01$ as variability criterion.

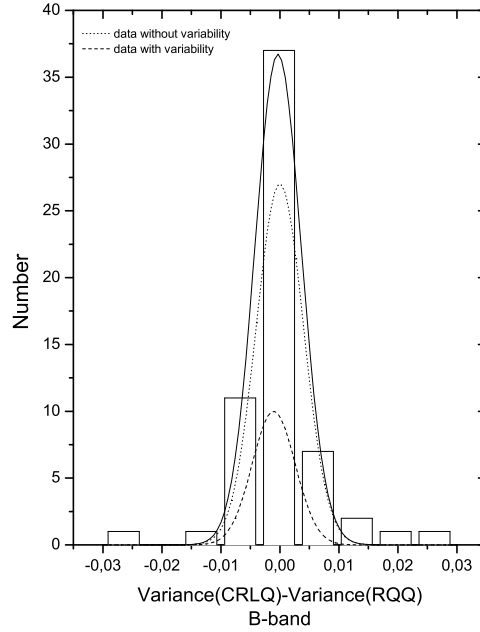
4.2. Quantitative Test for Differences between RQQs and CRLQs

Although the test for homogeneity did not show differences for the occurrences of OM between RQQs and CRLQs, a test on the quantitative values of the variance for both samples of objects might show whether the OM is larger in one type than in the other. The color changes during variations make it interesting to consider observations of each band separately.

In Paper I we showed that it is better to estimate the difference between RQQs and CRLQs breaking the variance into two components than considering a single observed variance. The intrinsic variance for a source, V_r , can be written as $V_r = V_o - e^2/5$, where V_o refers to the observed variance and e^2 are the squared errors of the data weighted by the number of observations in each group (five). The last refers to the inherent error of the observation and reduction data processes, and it is calculated empirically from the variance for each of the five observation groups.

The *t-Student* test can be used to find differences between the means when these have a normal distribution. This is approximately the case for the intrinsic variances difference. For these data, we have computed the *matched pair test*, in which the mean of the distribution of these difference should not be significantly different from zero if both samples are extracted from the same population. The test indicates that there are no significant differences among the samples: it gives a probability that the observed differences occur by chance of 18.7% for *B*, 19.1% for *V* and, 87% for *R*. When an independent pair test is carried out, the mean difference values are similar, within the errors, and so are the uncertainties of such differences.

This test was repeated considering average values of the intrinsic variances for each pair of objects. The qualitative result remains the same, however quantitative results do change: in *V*, the probability that the observed differences happen by chance increases to 28%, in *B* changes to 23% and in *R* it diminishes to 53%. The averages in this case are distributed so that the fits are quite good, because although we have lost *degrees* of freedom, the data of the variations themselves are masked when they are averaged with other data. It is nec-

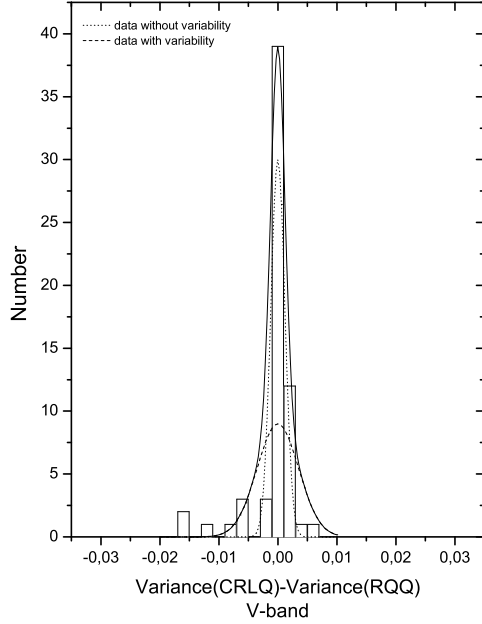


(a)

Fig. 2.—: Histogram for the intrinsic variance differences among CRLQ and RQQ paired. The continuous line represents the result of adjusting the mixture of two normal distributions to the data without detected microvariability (dotted line) and those with detected microvariability at least in a single band (dashed line).

essary to note that the probability obtained for the data of the *V* band is consistent with the value obtained in Paper I, where the same filter was used. These results imply that the incidence of OM is independent from luminosity and redshift.

The tests neatly point out to an extremely small and non significant difference in the microvariability displayed by the two samples, yielding no evidence that they come from different populations. Figures 2(a), 2(b) and 2(c) show the histograms for the intrinsic variance differences of the observations paired for each filter. Except in the case of *R*, for which data can be fitted using a single Gaussian profile with standard deviation of 2.3×10^{-3} and an average value of ~ 0 , the others cannot be accurately fitted by a single Gaussian. Taking

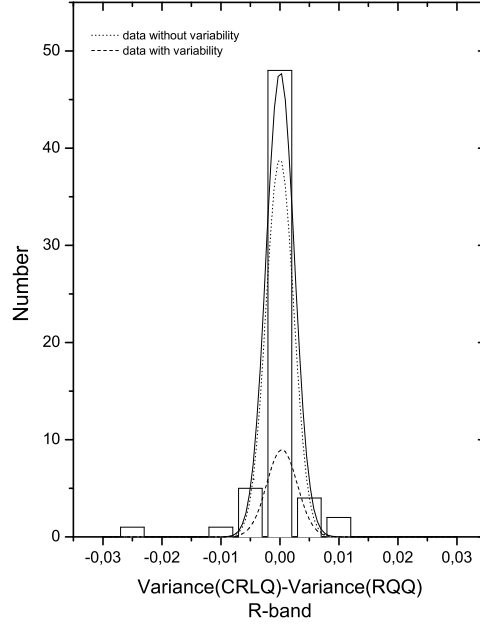


(b)

Fig. 2.—: Continued.

into account the results presented in Paper I, we separated the data into observations with (dashed line) and without (dotted line) detected variations. Then, good fits are obtained. As in Paper I we found that some variations could occur and not been detected. An OM event could occur in the three bands even if it is detected in only one.

In the B band, the data group where OM was not detected is centered in ~ 0 , and it has a standard deviation of 4×10^{-3} , i.e., indistinguishable from zero (Figure 2(a)) while, the group with variability has a standard deviation of 4×10^{-3} and is centered at 1×10^{-3} . These results indicate that the samples are not statistically distinguishable. In V there is a similar behavior (Figure 2(b)). The non variable component was fitted with a Gaussian that has a standard deviation of 1.2×10^{-4} and is centered on 4×10^{-4} , while the variable component is centered at ~ 0 and has a standard deviation of 4×10^{-3} . The data with OM detection were fitted by a Gaussian centered on 4×10^{-4} with standard deviation 3×10^{-3} , while the non



(c)

Fig. 2.—: Continued.

detection data were best fitted with a Gaussian centered on 0 with standard deviation 2.3×10^{-3} (Figure 2(c)). These results can change when we consider that some quasars were observed in more occasions than others.

All the statistics discussed here indicate that there are no significant differences in the OM properties between CRLQ and RQQ. While this is at odds with some other studies, it is consistent with the results reported in Paper I, by Stalin et al. (2004), and by Gupta & Joshi (2005).

4.3. Sample Selection and Duty Cycle

We can characterize the probability with which an OM event is detected as a function of the duration of the monitoring. The Duty Cycle (DC) is a very useful tool to compare the behavior of different types of AGN, and to plan future observations. The DC is defined as the ratio of the number of observations with a positive detection of OM to the total number of observations, weighted by the

period of time during which the objects have been observed (see Romero et al. 1999). Of course OM depends also on intrinsic causes that determine its occurrence. The last however, are unpredictable and unquantifiable. OM is believed to be a transient phenomenon. Independently of its origin, neither thermal nor non-thermal instabilities are expected to be permanent. We have calculated the DC using expression (2) from Romero et al. (1999), but considering the joined observations for RQQs and CRLQs, because we detect no difference between both samples. When the DC is calculated without taking into account the band, a value of 8.45% is obtained. If marginal detections are considered, the value does not change too much: 10%. Separating data by band, we obtain $DC_B = 2.3\%$; $DC_V = 6.8\%$, and $DC_R = 5.8\%$.

The DC_V is three times lower than the one reported in Paper I, where the same filter was used. The discrepancy could be due to the use of three filters in the present study. When we analyze the light curves from Paper I, we can see that one third of the events correspond to variations with constant increase or decrease. The rest correspond to changes with oscillating behavior. If this proportion is a general behavior, and since we have now a lower temporal covering, we expect to detect only the *constant* changes, i.e., a third of all the possible detections with one filter.

For the blazar class, Sagar et al. (2004) reported a $DC = 72\%$, and Gupta & Joshi (2005) reported $DC = 60\%$, for microvariability; while, Carini (1990) reported a DC of $\sim 80\%$ for timescales from hours to days. For the quasars Stalin et al. (2004) calculated a $DC_{RQQ} = 17\%$, and $DC_{RLQ} = 15\%$. Their observations were carried out in the R band. Using the data from table 4 of Paper I, and the expression of Romero et al. (1999), a DC of 18% is obtained for the join of RQQs and CRLQs samples.

Other groups have found differences in the Duty Cycle of these objects. Romero et al. (1999) calculated a DC of 68% and 6.9% for RL and RQ objects, respectively (their observations were carried out with a V filter). Taking the data of Jang & Miller (1997), the $DC_{RQQ} = 7.6\%$ (their observations were carried out with a R filter), while $DC_{RLQ} = 60.6\%$. With the data from Gopal-Krishna et al. (2000), $DC_{RQQ} = 6.1\%$ (not taking into account their detections that at

least are *very probable*, while when including those *probable detections* $DC_{RQQ} = 29.4\%$). These results show a clear difference between radio loud and radio quiet quasars, which represents a behavior very different to the one found in the present study.

At this point we want to stress the relevance of a good sample selection. However, all these groups included BL Lac objects among the RLQ samples, and it is very possible that this can alter the value of the DC for the RL sample. The DC for the RQQs on the other hand are very similar ($\sim 6 - 7\%$) to that found by us (for the complete sample). To illustrate this point, we point out that Romero et al. (1999) use a sample of RL objects that includes several BL Lac objects. 53% of their observations and 67% of their microvariability detections, correspond to blazar type objects. On the other hand, the RQQs sample of Jang & Miller (1997) is constituted mainly by non OM objects, since it is conformed by 90% of low brightness quasars. The average magnitudes for RQs are similar to the average magnitudes for RLs (averages only differ in 2%), but the average redshifts are much smaller for RQs (average redshifts differ in 62%; for RQQ z average is 0.5 while z average for RLQ is 1.3). Although in Paper I we have not found evidence of dependence of OM on brightness and/or redshift, it would be necessary to investigate further such possible biases. The non homogeneous samples problem could also be present in the work of Gopal-Krishna et al. (2000). These authors report observations of RQQ, without a control sample, comparing with their previous results on radio loud objects.

It is also worth noticing that, when the above authors make a sub-selection of objects with the selection criteria described here and in Paper I (except for the use of lobe dominated radio quasars instead of CRLQ), they obtain similar comparative results to those reported in Paper I (see also Stalin et al. 2004).

Finally, in Paper I we developed an alternative method to calculate the Duty Cycle. This method considers that all the quasars present the same DC in H hours of monitoring. We grouped the data in parcels according to monitoring duration, with intervals of 1 hour. Parcels larger than 6 hours have been excluded from the sam-

pling since they were very few for a good statistics. Using the current data in the equations 1, 2, and 3 from Paper I, we get that the mean value for the probability of detecting an OM event in 1 hour of monitoring, P_1 has a value of $8.9 \pm 2\%$, which is marginally different from the value found in Paper I ($P_1 = 5 \pm 2\%$, however take also account the fact commented above that in this study the detection of oscillating variability may be dumped by the larger lags in the monitoring). Table 3 is similar to Table 4 in Paper I. Columns show, respectively, the values of the number of monitoring hours, H ; the number of monitors in H hours, N_H ; the number of OM events detected in H hours, E_H ; the probability of detect an OM event in H monitoring hours, P_H ; and the probability of detection in 1 monitoring hour, P_1 .

4.4. ANOVA and χ^2 Tests

To illustrate the reliability in the use of ANOVA, additionally we have applied a test χ^2 to the data. The average, B_i , has been taken from each group of five observations, and the error, s_i , is obtained from the dispersion of these five observations. Table 4 shows the differential photometric data for each group of observations (t_1, t_2 and t_3 of US 3472). Taking the whole data set mean, $\langle B \rangle$, we can obtain the statistical

$$\chi^2 = \sum \frac{(B_i - \langle B \rangle)^2}{s_i^2}$$

As example, we see the case of US 3472 for the V band. Please note that we are carrying a large number of decimal places during the calculations. For this quasar we have the following values obtained from differential photometry, comparing with a stars field

$$B_1 = 0.5602 \pm 0.00206,$$

Table 3:: Duty Cycle				
H	N_H	E_H	P_H	P_1
1	9	1	0.111	0.111
2	21	1	0.048	0.024
3	53	5	0.094	0.032
4	25	2	0.080	0.021
5	17	0

$$B_2 = 0.5718 \pm 0.00116,$$

$$B_3 = 0.5808 \pm 0.0022.$$

From these values, the median is $\langle B \rangle = 0.57093$. Thus, we have $\chi^2 = 27.13095 + 0.5625 + 20.12746 = 47.82091$. As the tabulated value for χ^2 , with 2 degrees of freedom, for a level of meaning to the 0.1% has a critical value of 13.8150, we have detected variations at this level.

For the case of stars field, the raw differential photometric data is shown in Table 5, and the means are:

$$B_1 = -0.9446 \pm 0.00558,$$

$$B_2 = -0.9422 \pm 0.00256,$$

$$B_3 = -0.9466 \pm 0.00216,$$

which median is $\langle B \rangle = -0.94447$. With this, we have $\chi^2 = 0.000542773 + 0.78627 + 0.97242 = 1.75923$.

For comparison, using ANOVA the sum of the differences of the averages of the data shown in Table 4 is 0.00107, while the square difference of the internal dispersion is 0.0002084. As the degrees of freedom are $k - 1 = 2$ and $N - k = 12$, we have $F = 30.80614203$. With a level of significance of 0.001, a value of 12.97 is obtained. With such result, we have a positive detection of OM.

With the same procedure for the field stars (Table 5), we obtain that the sum of the square difference of the averages is 0.0000485335, while the difference of the internal dispersion is 0.0008472. Thus, we have that $F = 0.34721671$.

This example illustrates that microvariability detections with ANOVA are at least as reliable as those that can be obtained using χ^2 . In our example, we could estimate errors for each observation in the χ^2 test from the same quasar dataset, because the observations were performed

Table 4:: US 3472 minus star 3 data

t_1	t_2	t_3
0.558	0.571	0.583
0.564	0.570	0.585
0.555	0.569	0.585
0.558	0.575	0.576
0.566	0.574	0.575

using an ANOVA design. This is not usually the case with error estimates in χ^2 based designs. In χ^2 tests, errors are usually calculated either from different data sets (one or more comparison stars) (e.g., Romero et al. 1999) or from IRAF theoretical errors multiplied by a correction factor (e.g., Stalin et al. 2005). Besides, this estimated error is often considered as a constant along the dataset, missing the internal variability of the data due to short timescales factors (tiny clouds, seeing changes, etc.). By contrast, ANOVA uses internally consistent errors calculated from the same dataset.

5. SUMMARY AND CONCLUSIONS

We present a comparative study of the occurrence of OM in radio loud and radio quiet quasars using BVR bands. Following Paper I we stress the importance of sample selection criteria and observational methodology. Microvariability events were analyzed using *one-way* ANOVA test, reinforcing with a visual revision of the light-curves, and a χ^2 test. Five events were found in RQQs and four in CRLQs, with a significance level of 0.1% for a positive detection. Then, microvariability properties for each sample were compared using a χ^2 test for homogeneity. No significant difference among the samples was found, in agreement with the results obtained in Paper I.

Additionally, it was shown that both quasar types present the same quantitative microvariability properties. This is evidenced applying a *t-Student* test to the variance differences of each CRLQ-RQQ paired couple. Since quasars were paired by brightness and redshift, these properties do not influence the result. Moreover, these results do not differ when applying a statistical *t-Student* test for independence on the total observations, confirming the results reported in Paper I, i.e., that the evolution of the objects seems to

have little influence on microvariability.

Similar results have been found for long-term and intermediate-term variability (e.g. Webb & Malkan 2000; Vanden et al. 2004). The union of all these results, and the discovery of radio jets in RQQs (Blundell & Beasley 1998; Blundell & Rawlings 2001; Blundell et al. 2003) suggest that the OM source must be the same in both types of quasars, or at least very similar. This suggestion is reinforced by the detection of variations in radio frequencies for RQQ (e.g., Fanti et al. 1981; Mantovani 1982; Blundell et al. 2003).

Finally the Duty Cycle (DC; the percentage of monitoring time that an AGN shows variability) was calculated. This probability is 2.3% in the *B* band, 6.8% in the *V* band, and 5.8% in the *R* band. Without separating data by filter, DC=8.45% is obtained. These differences of DC between bands might arise from spectral variability during the MO events.

Results obtained by Jang & Miller (1995, 1997), Gopal-Krishna et al. (2000), and Romero et al. (1999) indicate that microvariability could be related to radio emission properties of the quasars. However, these results are probably biased due to sample selection criteria (see 4.3). On the other hand, it has been shown that with selection criteria similar to those discussed in Paper I, Stalin et al. (2004) and Gupta & Joshi (2005) obtain compatible results with those of the present paper.

As our results seem to indicate that the optical microvariability does not depend on the radio-properties of quasars, we would not exclude the possibility that it can have a similar origin in both RLQs and RQQs (at least for the commonly defined ranges). Although this would be an important result, deriving from comparative studies, we would still have the additional problem to establish unambiguously the origin of the microvariability. The possibility of a symbiosis disk-jet phenomenology (e.g., Falcke et al. 1996) can complicate any analysis, since instabilities (that produce variability) originated in the inner disk can be propagated to the jet (e.g., Gupta & Joshi 2005; Wiita 2005).

In a forthcoming paper (Ramírez et al. in preparation), we shall address this issue using our multiband data. Events arising in the accretion disk are

Table 5:: US 3472: star 3 minus star 6 data

t_1	t_2	t_3
0.952	0.944	0.948
0.959	0.933	0.939
0.936	0.948	0.951
0.928	0.945	0.95
0.948	0.941	0.945

expected to show a thermal signature, while jet perturbation events should be dominated by non-thermal processes. Thus the spectral evolution during a change of brightness, in other words, a color variability analysis can allow us to differentiate thermal from non-thermal origins.

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